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ANALYSIS OF HEAT MIGRATION INTO A CHAMBERED ROUND

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13. ABSTRACT *(Maximum 200 words)*
The temperature distribution within the charge of a tank round after its insertion into the gun breech is analyzed using an implicit finite-difference model. The propellant average temperature of the last of a series of rounds is determined as a function of the in-chamber time for a firing rate of six rounds/minute. The effects of propellant temperature, ambient temperature, previous number of rounds fired, and external convection heat transfer coefficient are presented.

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INTRODUCTION

This report documents the analytical study of the temperature changes to the propellant of a tank round after it has been inserted into the breech of a "hot" tank gun. The temperature of the tank gun increases as consecutive rounds are fired. This analysis focuses on the temperature profile within the last round, after it is inserted, but before it is fired. It is desirable to understand more about the changes to the propellant temperature under these circumstances, as these changes may affect the accuracy of targeting.

MODEL ASSUMPTIONS

A model has been developed to represent the propellant temperature distribution as a function of time. The special features of the model are as follows:

- The chamber and the round are considered to be "long," so that the conduction is purely radial through the breech wall and through the round charge.
- The heat transfer on the outer surface of the breech is due to free convection.
- The ambient is the interior environment of the turret.
- The charge temperature is uniform throughout, upon insertion into the breech.
- The thermal properties of the charge are the best available mathematical estimate for particulate charge materials of the M829A2 ammunition, which uses JA2 propellant.
- The initial radial temperature distribution in the chamber was based on the Benet Technology Team data, which also allowed for axial variations. The "worst case" axial location was chosen for our model.
- The thermal resistance of the gap between the round and the barrel was not modeled. The results represent the upper bound prediction of the heat going into the propellant bed.

MATERIAL PROPERTIES

The model contains a number of variables that represent properties specific to JA2 propellant and the properties specific to gun steel. The charge and steel variables of interest are density, specific heat, and thermal conductivity. The values for gun steel were readily available at Benet; however, finding information regarding JA2 proved to be much more challenging. After much research, values have been obtained for solid JA2 material. The JA2 in this ammunition is in granular and/or stick configurations. The values for solid JA2 needed to be adjusted mathematically to compensate for the amount of air (or void fraction) contained among the small pieces of the propellant. The void fraction was estimated to be 10% in this analysis. The solid values of density and specific heat have been modified using this value. The equations for the void fraction analysis are as follows:

$$f_a = V_a/V_t \tag{1}$$

The mass of the charge is

$$m_c = \rho_a V_a + \rho_c V_c \tag{2}$$

Using the above two equations, the average density of the charge is derived as

$$\bar{\rho}_c = \rho_a f_a + \rho_c(1 - f_a) \tag{3}$$

The average specific heat of the charge is derived in a similar manner and is

$$\bar{c}_p = c_{pa}\rho_a f_a + c_{pc}\rho_c(1 - f_a)/(\rho_a f_a + (1 - f_a)\rho_c) \tag{4}$$

The mean diffusivity is then

$$\bar{\alpha}_c = \bar{k}_c /(\bar{\rho}_c \bar{c}_{pc}) \tag{5}$$

where

$$\bar{\rho}_c \bar{c}_p = c_{pa}\rho_a f_a + c_{pc}\rho_c(1 - f_a) \tag{6}$$

During a previous project at Benet Laboratories, a value for thermal conductivity for granular JA2 was obtained experimentally as 0.0774 Btu/(hr-ft-°F). This value was used in this analysis.

MATHEMATICAL MODEL

As stated previously, the mathematical model of the propellant is one- dimensional, where the radial position is the independent variable. The model uses implicit finite-difference equations and a fixed time step. The propellant/gun radial distance is broken into a number of nodal positions as seen in Figure 1. The nodes are characterized by equations, which can be categorized as follows:

- The center node
- The interface node
- The exterior node
- The interior nodes

The center node is the radial center of the charge. The interface node is the radial location of the interface between the round and the gun. The exterior node is the radial location of the outside diameter of the breech. The interior nodes are all other radial nodes located either within the propellant or the gun. The nodes are equally spaced by Δr with one exception; the distance from the center node to the next node is $\Delta r/2$.

Using conservation of energy, the heat going into each node is

$$q_{in} = q_{storage} + q_{out} \tag{7}$$

The equations for the various nodes are derived by applying the conservation equation to each elemental shell. The derived equation for the interior shell nodes is

$$T_m^p = (1+2Fo_x)T_m^{p+1} - Fo_x[(1+(\Delta r_m/2r_m))T_{m+1}^{p+1} + (1-(\Delta r_m/2r_m))T_{m-1}^{p+1}] \tag{8}$$

where

$$Fo_x = (\alpha_x \Delta t)/\Delta r_m^{\ 2} \tag{9}$$

and x = a variable that represents either "b" for the gun steel nodal region or "c" for the propellant nodal region.

The equation for the exterior atmospheric boundary node is

$$\begin{aligned} T_m^p + 2Fo_b Bi T_\infty = {} & [1+2Fo_b Bi + 2Fo_b(1-(\Delta r_m/2r_m))]T_m^{p+1} \\ & -2Fo(1-(\Delta r_m/2r_m))T_{m-1}^{p+1} \end{aligned} \tag{10}$$

where

$$Fo_b = (\alpha_b \Delta t)/\Delta r_m^{\ 2} \tag{11}$$

and

$$Bi = (h\Delta r_m)/k_b \tag{12}$$

The equation for the interface shell node is

$$\begin{aligned} (1/2)[(1/Fo_c)+(k_b/k_c)(1/Fo_b)]T_m^p = {} & \{(1/2)[(1/Fo_c)+(k_b/k_c) \\ & (1/Fo_b)] + [(1-(\Delta r_m/2r_m))+(k_b/k_c)(1+(\Delta r_m/2r_m))]\}T_m^{p+1} \\ & -(1-(\Delta r_m/2r_m))T_{m-1}^{p+1} - (k_b/k_c)(1+(\Delta r_m/2r_m))T_{m+1}^{p+1} \end{aligned} \tag{13}$$

The equation for the center node in the charge is

$$T_{m-1}^p = (1+4Fo_c)T_{m-1}^{p+1} - 4Fo_c T_m^{p+1} \tag{14}$$

The number of equations is equal to the number of nodes. The equations may be reorganized and put in matrix row form. The equations would then form the matrix equation as

$$[A][T]^{p+1} = [T]^{p} \tag{15}$$

Inverting the A matrix and multiplying through yields

$$[T]^{p+1} = [A]^{-1}[T]^{p} \tag{16}$$

This formula is used iteratively in the thermal emulator software program to compute the radial temperature distribution in the charge/gun model as a function of time. The results of this program were validated using the Heisler charts.

The initial temperature distribution in the breech wall is an important feature, which affects the accuracy of the model. This distribution depends, in part, upon the firing scenario prior to insertion of the round and the ambient temperature conditions. Benet has a software program, FDHEAT, that profiles the gun temperature distribution when given the type of ammo, the type of gun, the firing rate, and the ambient temperature conditions. The results of this software program are used as initial conditions in the input temperature matrix of the thermal emulator program.

The average temperature of the propellant with respect to time is be derived from the temperature distribution as it varies with time. The equation for the energy stored in the propellant is

$$E_T = \Delta E_c + \sum_{m=c+2}^{m=i-1} \Delta E_m + \Delta E_i \tag{17}$$

The average temperature of the round at any point in time is be calculated as

$$T_{av} = T_i + E_T /(\rho_c c_{pc} V_t) \tag{18}$$

The average temperature of the charge as a function of time may be useful to the fire control engineers.

RESULTS

Figures 2 through 6 present a sample of runs including propellant average temperature versus time for various initial round temperature and gun temperature scenarios. Each graph has a plot for the average temperature in the last-loaded round after a certain number of rounds is fired. All scenarios have a constant rate of fire of six rounds per minute.

The graphs indicate that a heated chamber definitely causes a change in the average temperature of the propellant. The heat transfer is significantly affected by a number of variables, including the number of rounds previously fired and temperature of the round obtained from stowage. Figure 6 indicates that the convective heat transfer coefficient plays a significant role in that circulating air, as opposed to stagnant air, within the crew compartment increases the cooling process of the gun and therefore affects the propellant temperature.

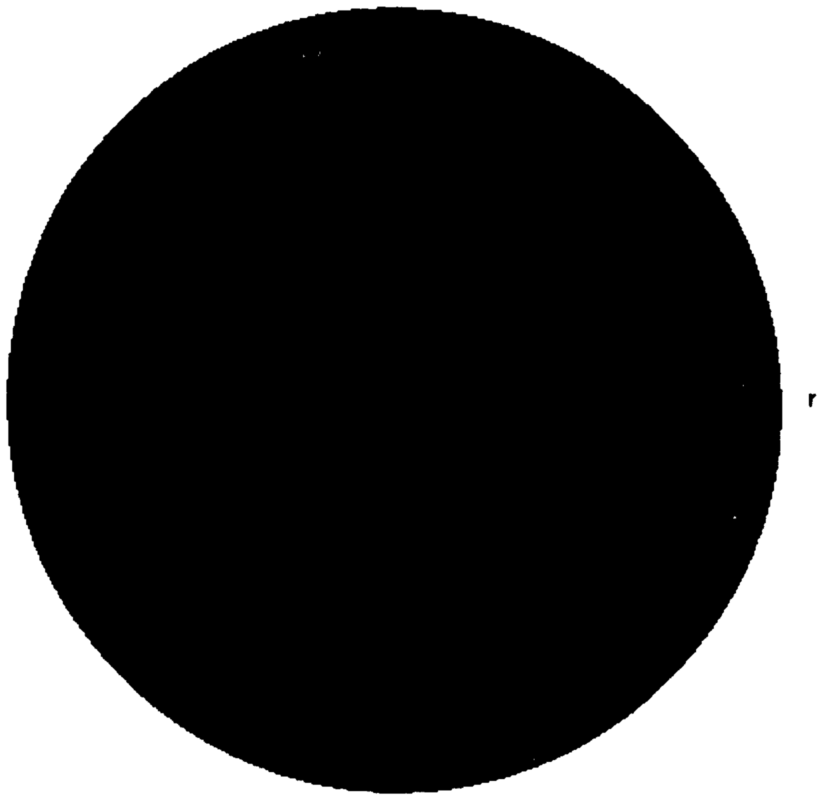

Figure 1. Cross-sectional view of propellant/gun node pattern.

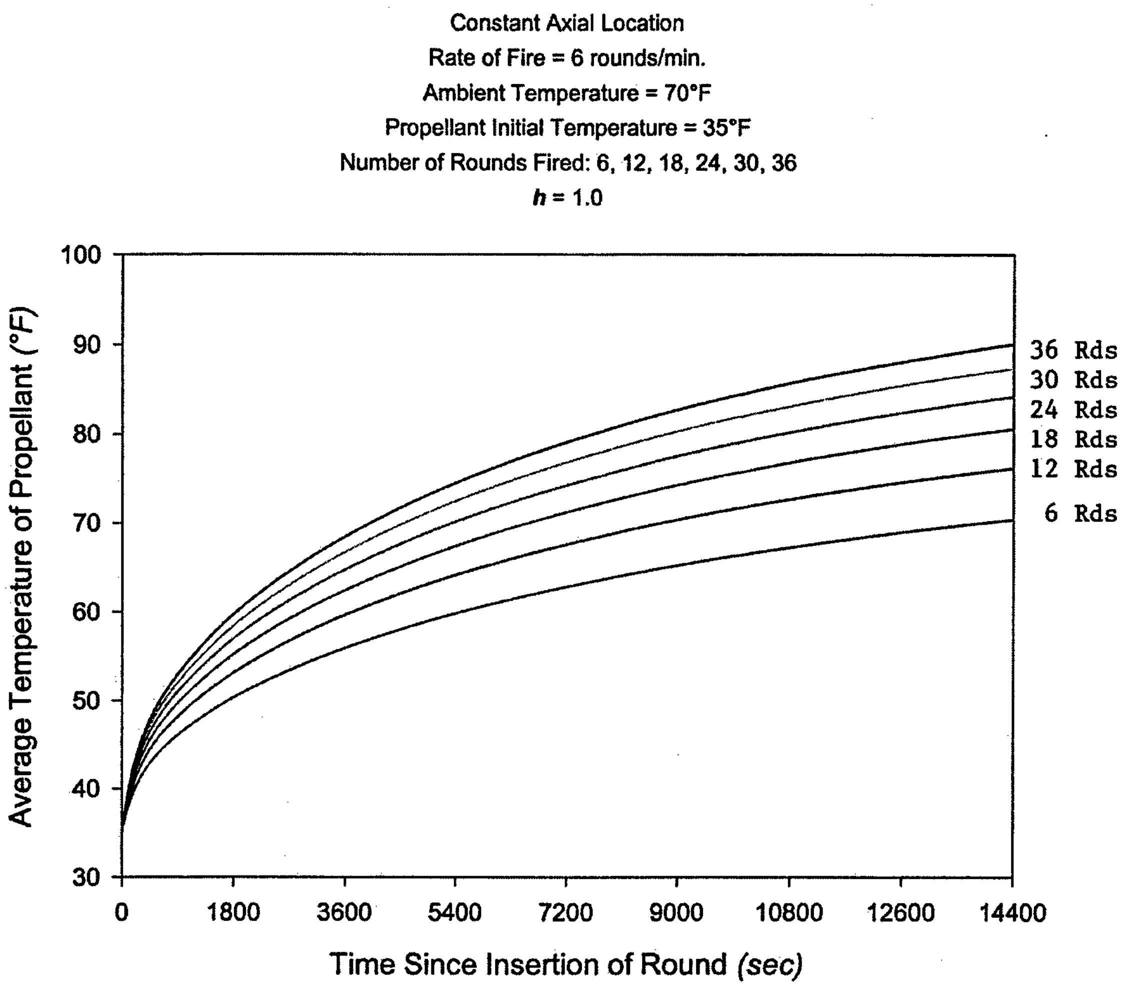

Figure 2. Propellant average temperature versus time with mild crew compartment temperature and cold round temperature.

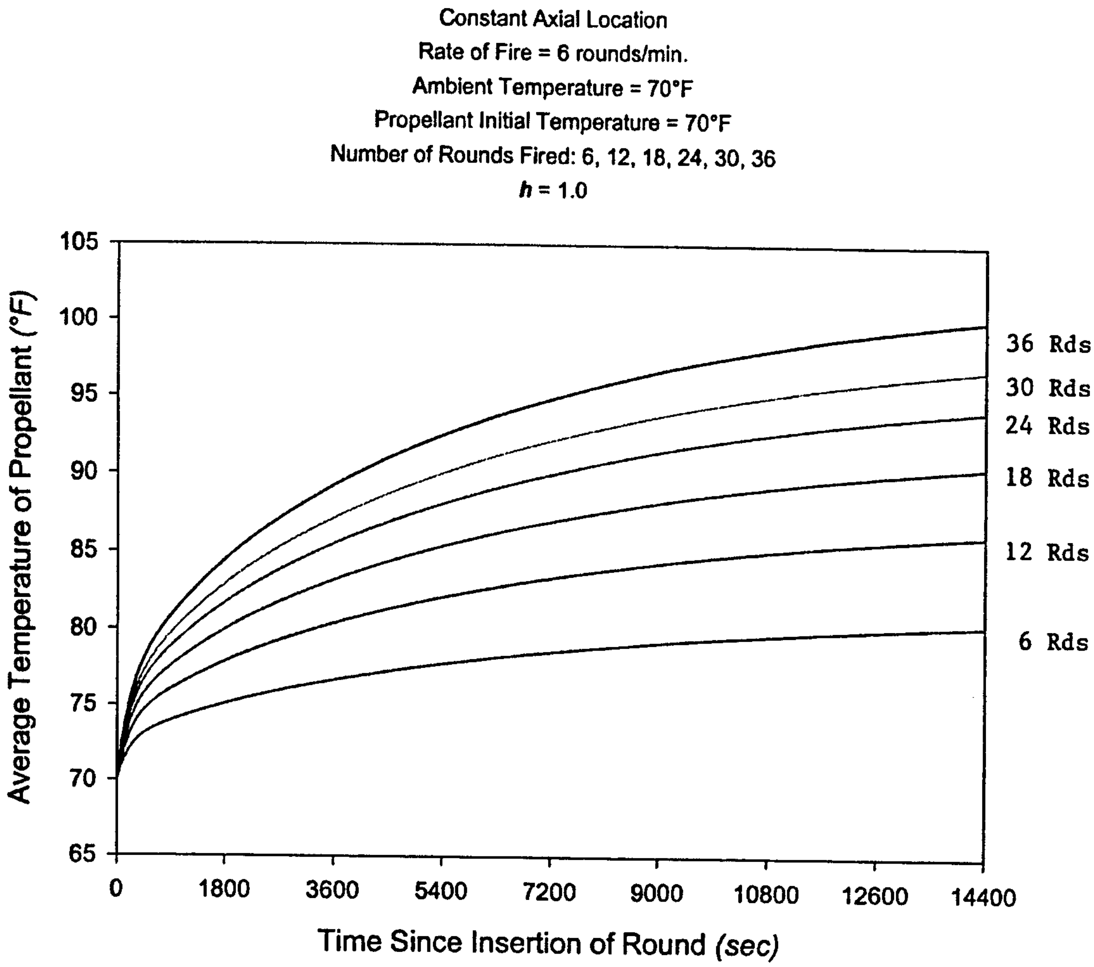

Figure 3. Propellant average temperature versus time with mild crew compartment temperature and mild round temperature.

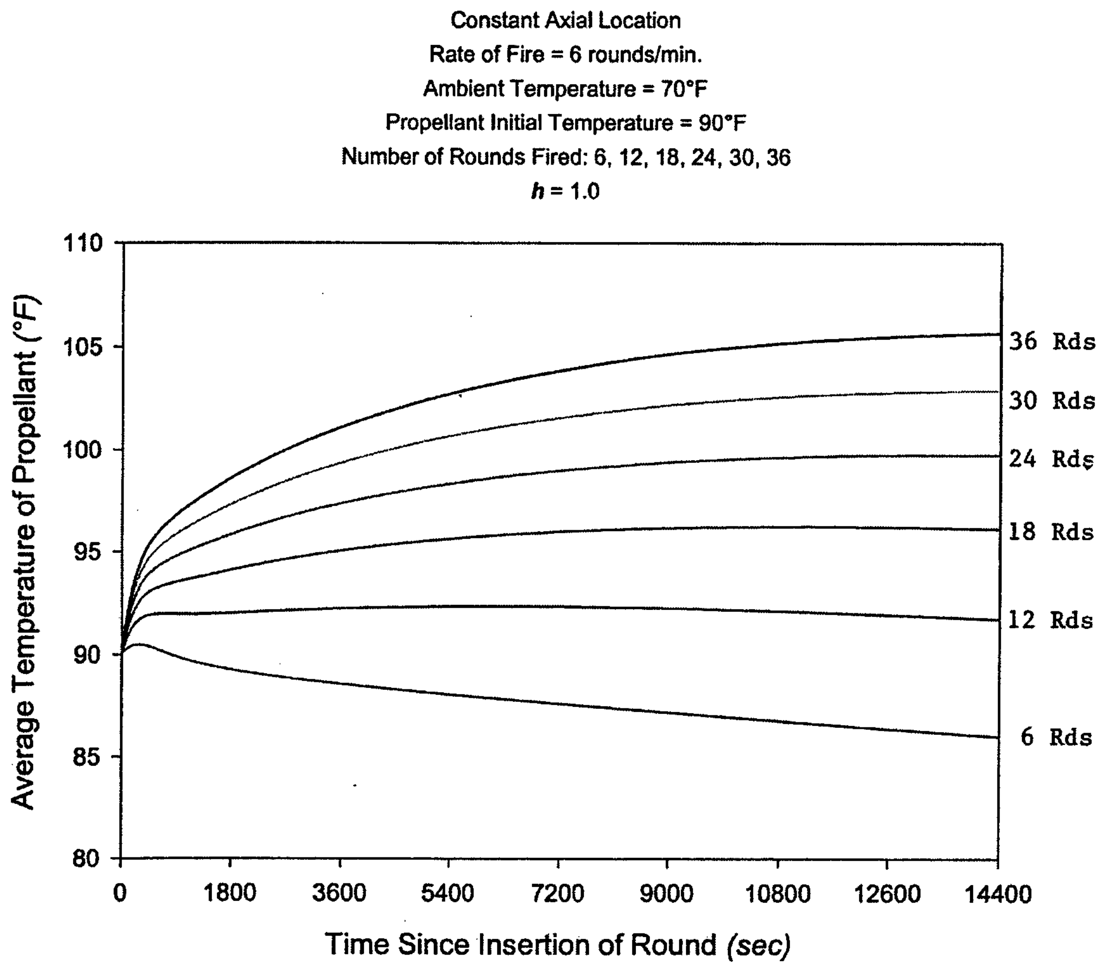

Figure 4. Propellant average temperature versus time with mild crew compartment temperature and hot round temperature.

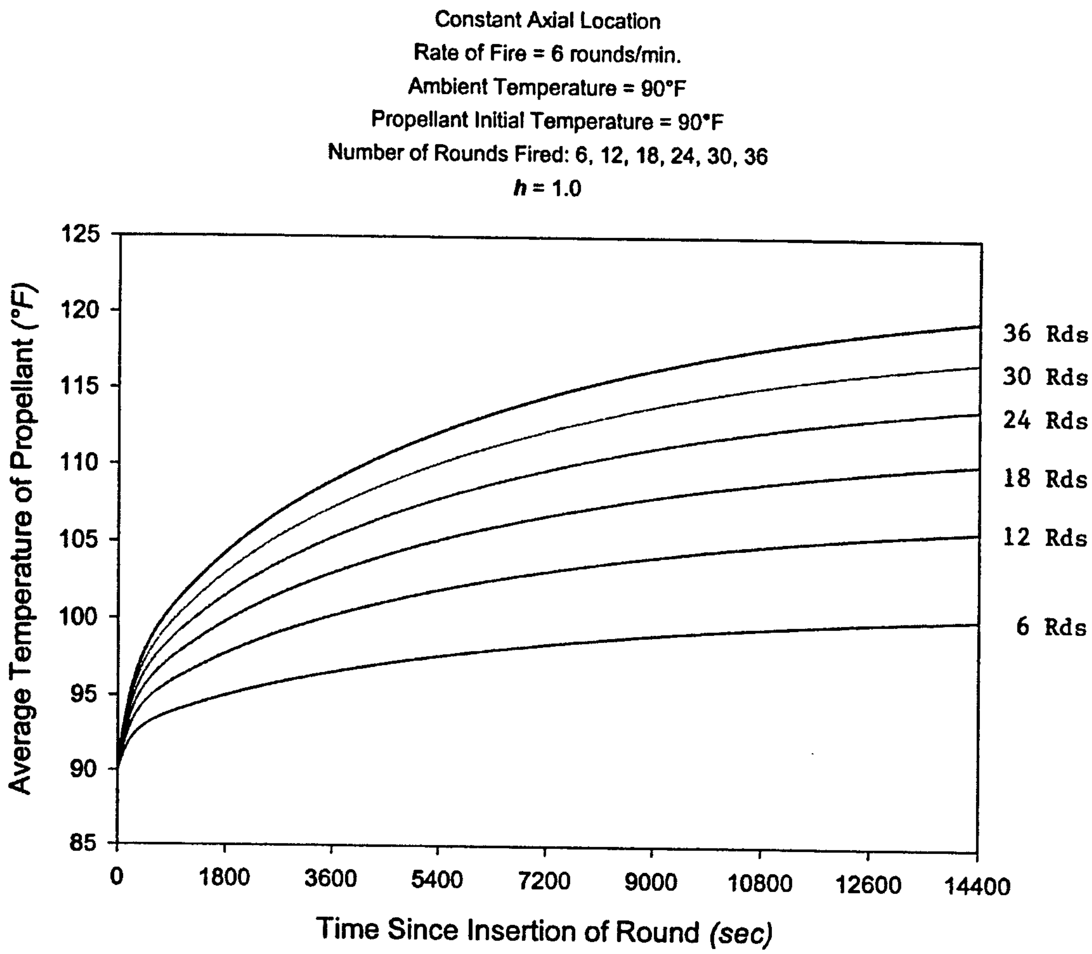

Figure 5. Propellant average temperature versus time with hot crew compartment temperature and hot round temperature.

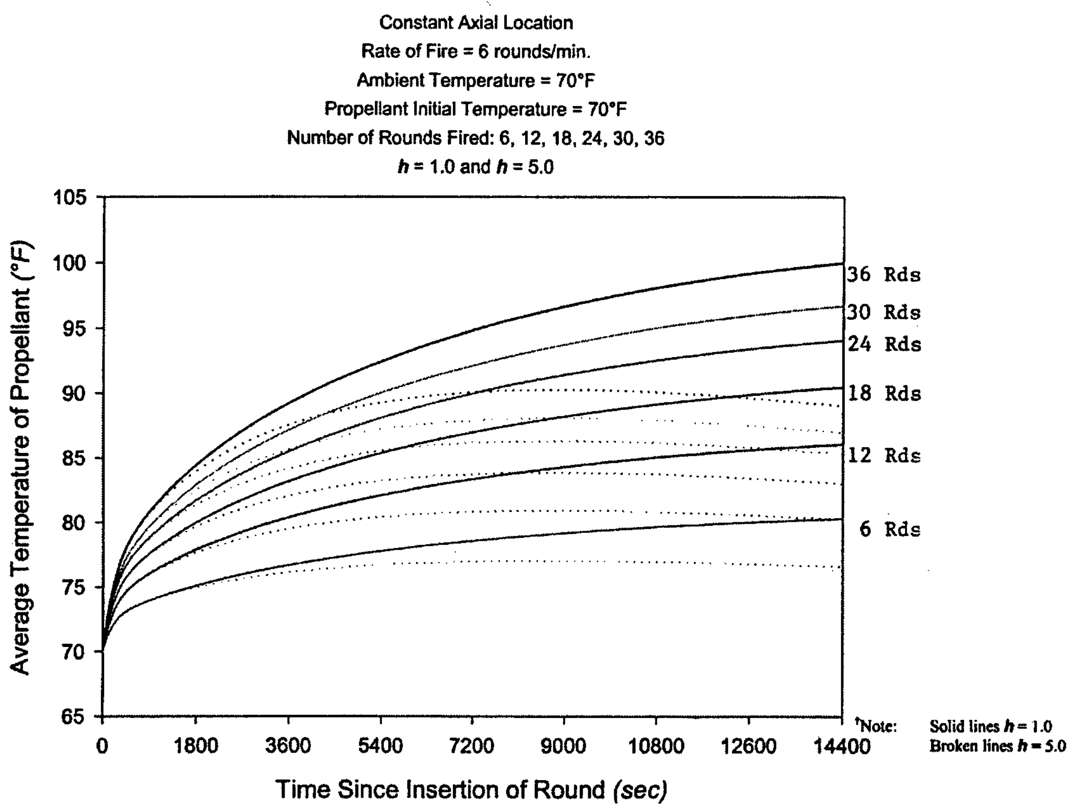

Figure 6. Propellant average temperature versus time with mild crew compartment temperature and mild round temperature at *h* equals 1.0 and 5.0.

NOMENCLATURE

The variables for the model are assigned as follows:

m	Node number
p	Beginning of time step
$p+1$	End of time step
Δr_m	Radial distance between consecutive nodes
r	Radial distance starting from center of charge
T	Temperature
$[T]$	Temperature matrix
m_c	Mass of charge
k_c	Thermal conductivity of charge
h	Free convective heat transfer coefficient
k_b	Thermal conductivity of breech (gun steel)
Bi	Biot number
α_b	Thermal diffusivity of breech (gun steel)
Fo_x	Fourier number of material x
α_c	Thermal diffusivity of solid charge
$\overline{\alpha}_c$	Average thermal diffusivity of charge
c_{pa}	Specific heat of air in the charge
c_{pc}	Specific heat of solid charge
$\overline{c}_{pc}$	Average specific heat of charge – air mixture
ρ_a	Density of air in the charge
ρ_c	Density of charge

$\overline{\rho}_c$	Average density of charge – air mixture
Δt	Time step
q	Heat flux rate
V_t	Volume of solid charge
V_a	Volume of air in charge – air mixture
V_c	Volume of solid JA2 material
f_a	Void fraction of charge
E_c	Energy contained in the center shell of charge
E_i	Energy contained in the outer shell of charge
E_T	Energy stored in the charge

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